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BIOLOGICAL PHOSPHORUS REMOVAL

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16. ABSTRACT

Three proprietary biological phosphorus removal processes are reviewed. The paper presents the description and development status of these technologies. The paper is a summary of the emerging technology assessment report published by U.S. Environmental Protection Agency in 1984. The processes reviewed are: 1) The PhoStrip process marketed by Biospherics, Inc., 2) Anaerobic/Oxic process marketed by Air Products and Chemicals, Inc., and 3) Bardenpho process marketed by Envirotech Corporation.

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INTRODUCTION

Control of nutrients discharged in wastewater plant effluents is an important consideration in protecting water bodies from excessive algae and aquatic vegetation growth. The negative aspects of algae growth such as taste and odor problems in water supplies, variation in water dissolved oxygen content during day and night, effect on the ability of certain fish species to grow, and impact on the recreational use of water are well documented. Strict effluent standards for nitrogen and phosphorus have been established for municipal wastewater discharges in many areas of the United States to minimize eutrophication problems. Examples are the Great Lakes regions, the Florida-Tampa Bay region, Lake Tahoe, and the Chesepeake Bay area. Typical effluent standards have been 1 g/m^3 and 3 g/m^3 for phosphorus and total nitrogen, respectively.

Chemical precipitation has been the most widespread method to accomplish phosphorus removal from wastewaters using either lime, alum, or ferric chloride. The disadvantage for this phosphorus removal method is the increased sludge production, continual chemical cost, chemical storage requirements, chemical handling requirements, and chemical feed control requirements. Biological phosphorus removal provides an alternative to chemical treatment methods. The economics of biological or chemical phosphorus removal are dependent upon the influent phosphorus concentrations, as well as other wastewater characteristics, and effluent requirements. The influent phosphorus concentration in wastewaters depends upon infiltration, the use of low phosphorus detergents, and industrial wastewater contributions. Influent phosphorus concentrations vary from 3.5 to 12.0 g/m^3 (1).

Phosphorus in raw wastewaters exist in three forms; ortho (PO_4), polyphosphates (P_2O_7) and organic phosphorus. The orthophosphate can be readily assimilated by microorganisms and the polyphosphates and organic phosphates are usually hydrolyzed by microorganisms to the ortho form. The polyphosphate and organic phosphorus content may account for 40 to 70 percent of the phosphorus in wastewaters. Secondary biological treatment systems accomplish some phosphorus removal by the use of phosphorus for cell synthesis during BOD removal. A typical phosphorus content in sludge from biological systems is in the range of 1.5 to 2 percent based on dry weight. The amount of phosphorus removed due to sludge wasting may be in the range of 10 to 30 percent of the influent amount. This is affected by sludge handling techniques and side stream return flows.

Prior to the present application of specifically designed biological phosphorus removal systems, a series of studies and full-scale plant observations on biological phosphorus removal had been reported. In 1955, Greenburg et al. (2) proposed that activated sludge could take up phosphorus at a level beyond its normal microbial growth requirements. Srinath et al. (3) reported in 1959 that soluble phosphorus in mixed liquor (aqueous phase) decreases rapidly to below 1 mg/L under varying conditions of aeration. However, Levin and Shapiro (4) in 1965 were the first to associate excess biological phosphorus removal, now called "luxury uptake," with anaerobic/aerobic sequencing of biological treatment systems, which is currently the accepted mechanism. This led to intensive studies of the possible application of this phenomenon for removal of phosphorus in activated sludge

plants (5,6,7,8,9). It appeared that all the plants that successfully removed phosphorus were high-rate, non-nitrifying, plug-flow type activated sludge plants. By the early 1970's, three distinct proprietary biological phosphorus removal processes had been developed; namely, the PhoStrip process by Levin et al. (10,11,12), the Bardenpho process by Barnard of South Africa (13,14), and the A/O process by Air Products and Chemicals, Inc. (15,16). These three commercial biological phosphorus removal processes are currently patented and marketed in the United States by the following companies:

- PhoStrip - Biospherics, Inc.
- A/O - Air Products and Chemicals, Inc.
- Bardenpho - EIMCO Process Machinery Division of Envirotech Corporation

In this paper these three processes will be reviewed. The review is a summary of an EPA Emerging Technology Assessment Manual published in May 1984 (17). For further details the reader is referred to this publication.

PHOSTRIP PROCESS

The PhoStrip process was first proposed by Gilbert Levin in 1965 (4,5) and is currently marketed by Biospherics, Inc. This process is an activated sludge process that takes advantage of "luxury" phosphorus uptake and anaerobic phosphorus release. A schematic flow diagram of the PhoStrip process is presented in Figure 1. This process differs from conventional activated sludge in that a portion of the return sludge is subjected to "phosphorus stripping" by holding the sludge under anaerobic conditions in a stripper tank. The solids retention time (SRT) in this tank typically ranges from 8 to 12 hours. During this anaerobic period, phosphorus is released and is elutriated from the sludge in the stripper tank with a stream that is low in phosphorus content. This stream may either be the overflow from the chemical treatment tank (reactor clarifier) as is shown in Figure 1, or primary effluent. The phosphorus-rich overflow from the stripper tank passes continuously to the chemical treatment tank where lime is added for phosphorus precipitation.

Because of the flexibility of the percent of return sludge that can be subjected to anaeoribic conditions for different detention times in the stripper tank, a wide range of phosphorus removal can be achieved. Control of the side-stream permits phosphorus removal to be divided between stripper supernatent and waste activated sludge (12).

Since 1965 many pilot studies and plant-scale demonstration tests had been conducted to substantiate the applicability of this process under various operating conditions. In addition, over a dozen full-scale plants employing the PhoStrip process have been constructed, many of them involving retrofitting of existing facilities. The results of the findings from the available pilot tests and plant-scale data are summarized below:

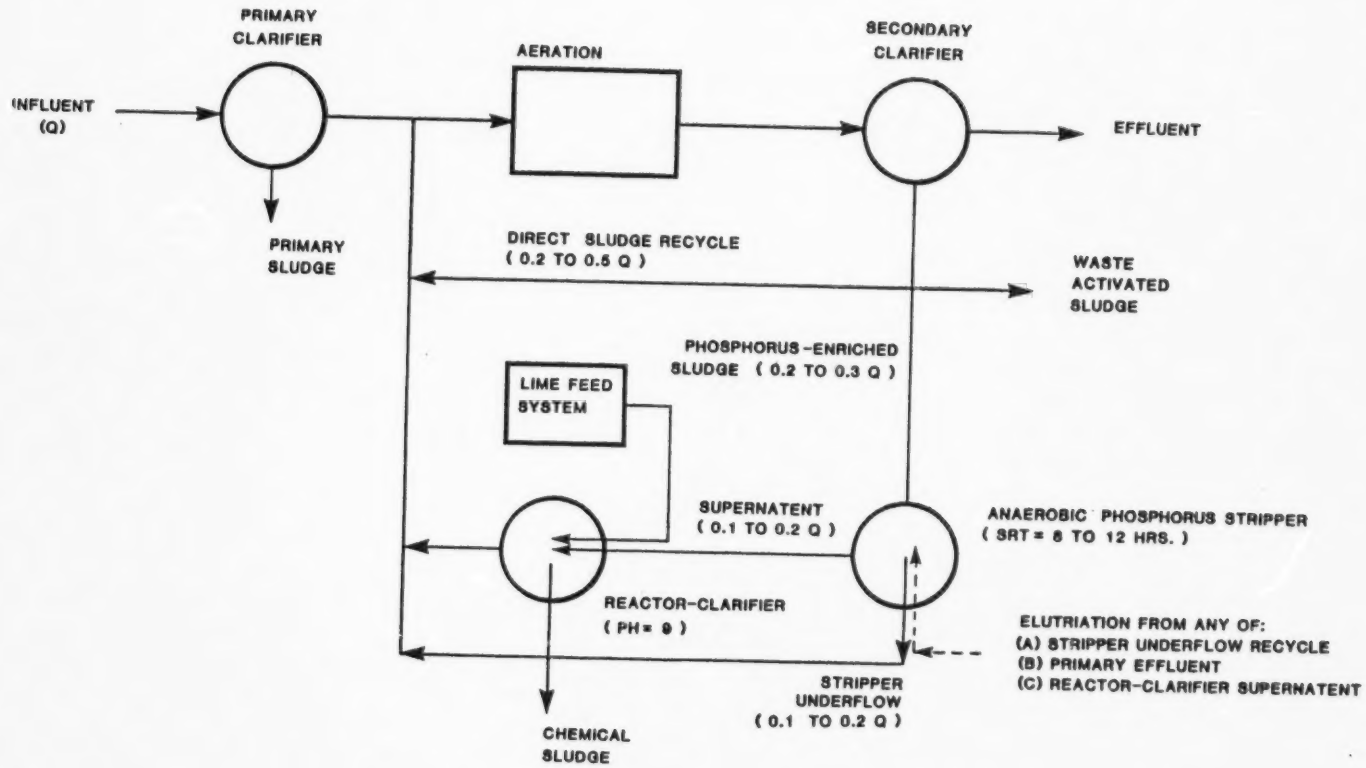

Figure 1. PhoStrip Process Flow Diagram

- The PhoStrip process is capable of producing effluent quality with total phosphorus (TP) of 1 mg/L, most of the time, without effluent filtration.

- Excursion of total phosphorus above the 1 mg/L level can happen due to high suspended solids discharged in the final clarifier effluent. Several plants include the use of effluent filters to assure that the effluent TP of 1 mg/L is met.

- The PhoStrip process is applicable to a wide range of activated sludge modes and various wastewater characteristics.

- The PhoStrip process requires less chemicals and produces less sludge than conventional mainstream treatment using lime addition for phosphorus removal.

The equipment used in the PhoStrip process includes concrete or steel tanks, mixers, pumps, and lime feed facilities. These are all conventional wastewater treatment facilities and are available from many competitive equipment suppliers. However, there have been many cases of mechanical difficulties observed during startup. There is need to provide a more reliable equipment package, particularly those related to transfer pumps, lime handling facilities, and automatic control instrumentation.

A/O PROCESS (ANAEROBIC/OXIC)

The A/O process was developed by Air Products and Chemicals, Inc. for the removal of phosphorus and/or nitrogen from wastewater (15,16). The A/O process is a suspended growth system that can combine anaerobic, anoxic[1], and aerobic sections in sequence. Figure 2 is a schematic representation of the A/O process for phosphorus removal. The process can be designed for phosphorus removal with or without nitrification and denitrification. All sections are partitioned into several hydraulic stages to approach plug-flow and prevent back-mixing. Typically, for removal of phosphorus, three anaerobic stages are followed by three or more aerobic or oxic stages. Recycled sludge from the secondary clarifier is mixed with either raw wastewater or primary effluent in the anaerobic section so that there is "sorption" of BOD by the organisms, with accompanying phosphorus release necessary for biological phosphorus removal. The anaerobic section is covered and equipped with mechanical mixers for mixing but not aeration.

The oxic stage, essential for the metabolism of BOD and uptake of the phosphorus released in the anaerobic stage, may be aerated with either air or oxygen. Phosphorus is removed from the system in the waste sludge, which may contain 4- to 6- percent phosphorus by dry weight. Effluent phosphorus concentrations are dependent on sludge wasting, which in turn is controlled by the plant's operating solids residence time (SRT).

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[1]The term "anaerobic" refers to environments that have no measurable concentrations of either dissolved oxygen or oxidized nitrogen in the form of nitrate or nitrite; "anoxic" refers to environments that have no dissolved oxygen, but can have oxidized nitrogen present.

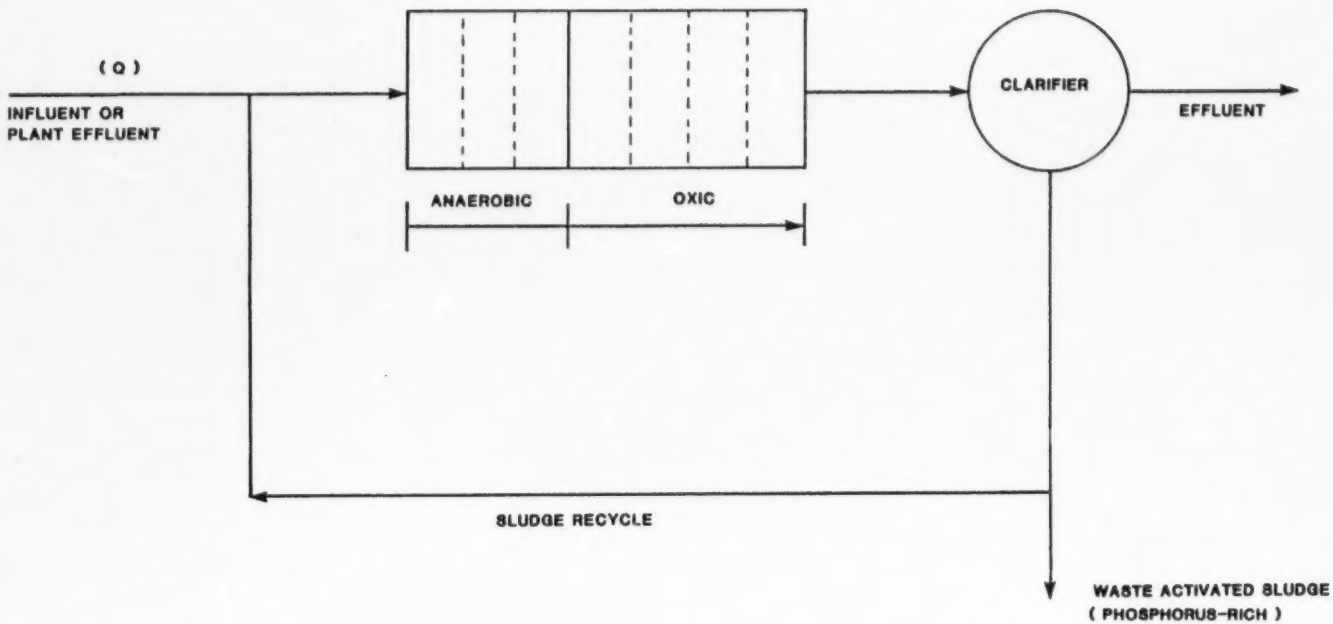

Figure 2. A/O Process Flow Diagram for Phosphorus Removal

When necessary, nitrification can be accomplished in the oxic section by operation at a properly selected solids residence time and organic loading suitable for growth of nitrifying bacteria. When denitrification is further required, the anoxic section is included between an anaerobic and oxic section as shown in Figure 3. The anoxic section is deficient in dissolved oxygen, but chemically-bound oxygen in the form of nitrate or nitrite is introduced by recycling nitrified mixed liquor from the oxic section back to the anoxic section.

In the 1970's, a number of laboratory-scale and pilot-plant tests have been conducted, including those at Bath, Pennsylvania; Washington, DC; Allentown, Pennsylvania; Rochester, New York; and Largo, Florida. The only plant-scale demonstration facility existing so far is the 3.0-mgd retrofitted portion of the plant at Largo, Florida. After completing pilot and plant-scale A/O studies, the City of Largo decided to expand their entire 9-mgd plant to 15 mgd. Full-scale A/O plants for several municipalities are currently in the design stage or under construction. The results of findings from the pilot and plant-scale tests are summarized as follows:

- Soluble ortho-phosphate can be reduced to less than 1 mg/L by the A/O system without nitrification in a relatively short detention time (less than 4 hours).

- Data from the Largo demonstration plant showed that the A/O system with nitrification produced effluent soluble phosphorus in excess of 1 mg/L during the first four months, but less than 1 mg/L after that period of acclimation. Ammonia nitrogen was generally reduced to less than 2 mg/L, which indicated that nitrification was quite effective. However, nitrate and nitrite levels in the treated effluent were in the range of 8 to 10 mg/L, which indicated that only partial denitrification was attained. The ability of the A/O system to achieve a high degree of denitrification and to produce effluent soluble phosphorus of less than 1 mg/L on a consistent basis remains to be demonstrated.

- The performance of the A/O system is dependent on the ratio of soluble BOD to phosphorus in the feed to the system; it will operate best when the ratio is greater than approximately 10 to 1.

- Phosphorus removal performance remained relatively stable as the operating temperature was decreased from 15°C to 10°C, and actually improved as the operating temperature was further decreased from 10°C to 5°C.

- The A/O system produces a phosphorus-rich (4.2 to 6 percent by weight) excess sludge which must be further stabilized before final disposal.

- Concentrations of total phosphorus (i.e., soluble plus suspended form) in the A/O effluent at Largo were in the range of 1.3 to 2.0 mg/L. The phosphorus concentrations were attributable to the total suspended solids (TSS) in the clarifier effluent. (For example, if

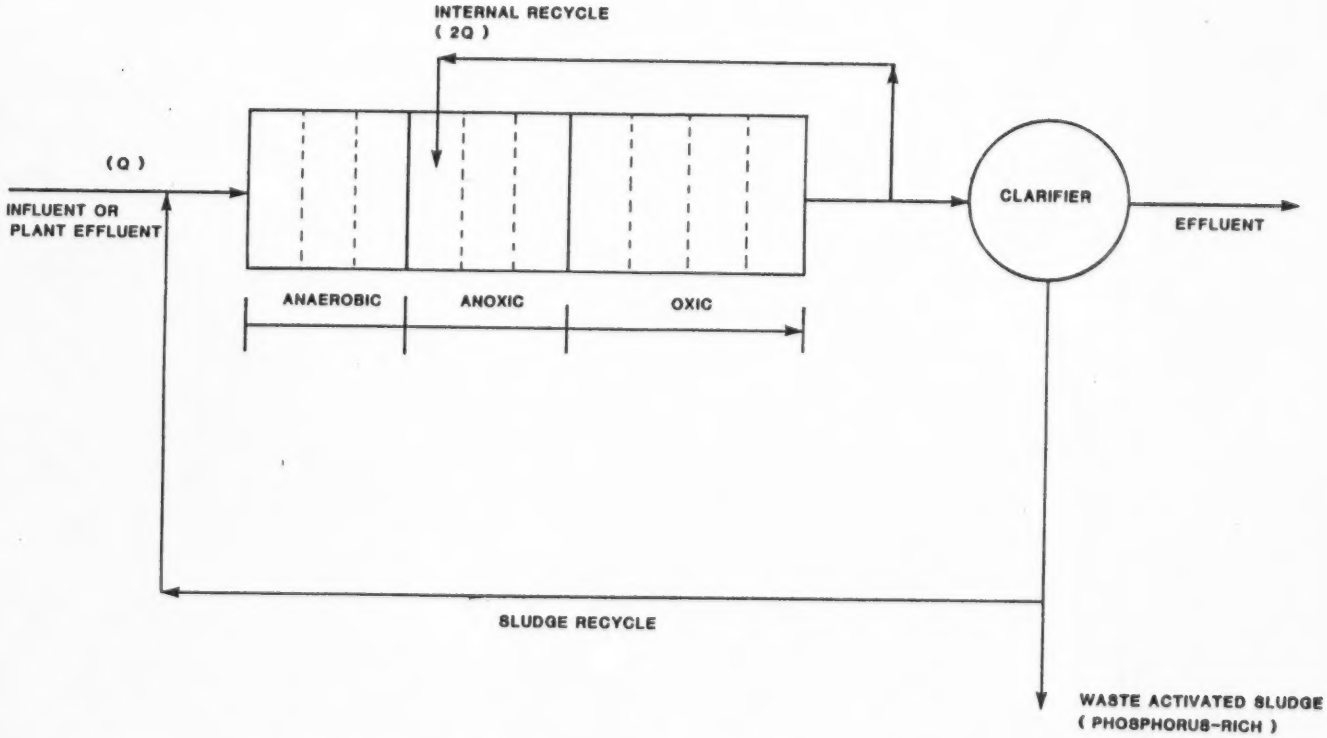

Figure 3. A/O for Phosphorus Removal with Nitrification/Denitrification

the TSS were 20 mg/L in the clarifier effluent and contained 5 percent of the P, the phosphorus in these solids would amount to 1.0 mg/L). Therefore, effluent filters will be necessary if effluent limitations call for total phosphorus not to exceed 1 mg/L.

- Chemical treatment may be required to reduce the amounts of phosphorus contained in the internal sidestreams, particularly in the case of supernatants from anaerobic digesters.

The equipment used in the A/O process includes concrete or steel tanks, mixers, aerators, clarifiers, and pumps for recycle and sludge handling. As in the case of the PhoStrip process, these are all conventional facilities available from many equipment suppliers.

BARDENPHO PROCESS

The Bardenpho process was first investigated in Pretoria, South Africa by James Barnard in the early 1970's (13). Bardenpho stands for Barnard-denitrification-phophorus, an activated sludge process designed to accomplish both biological phosphorus uptake and nitrogen removal. The process is patented by the South African Inventions Development Corporation and licensed to Envirotech Corporation for marketing in the United States. The Bardenpho process is very similar to the previously described A/O process, except there is an additional anoxic and a reaeration section at the tail end.

As shown in Figure 4, two anoxic stages are used to accomplish high levels of biological nitrogen removal by denitrification. An anaerobic stage is added ahead of the original four-stage Bardenpho nitrogen removal system to create anaerobic-aerobic contacting conditions necessary for biological phosphorus uptake. Return activated sludge, separated from the clarifier, is mixed with the influent wastewater prior to the anaerobic contactor, which is to initiate luxury phosphorus uptake by first releasing phosphate. Mixed liquor from the anaerobic contactor then flows into the first anoxic denitrification zone where it is mixed with an internally recycled mixed liquor from the aerobic nitrification zone. In the first anoxic denitrification zone, nitrate is reduced to nitrogen gas using soluble organic matter in the wastewater as a carbon source. The mixed liquor then flows into the aerobic nitrification zone where luxury phosphorus uptake, ammonia oxidation, and additional BOD removal occurs. Following the aerobic nitrification zone, a second anoxic zone provides additional denitrification, which is designed to remove additional nitrate and minimize nitrate feedback to the anaerobic contactor. The reaeration zone provides oxidation of remaining ammonia and raises dissolved oxygen levels for effluent discharge.

Phosphorus is removed from the system in the waste sludge, which may contain 4- to 6-percent phosphorus by dry weight. Depending on the relative amounts of phosphorus, BOD, and nitrogen in the influent, low levels of phosphorus (less than 1 mg/L) can be achieved in the effluent. For weaker wastewaters or high influent phosphorus concentrations, a small amount of

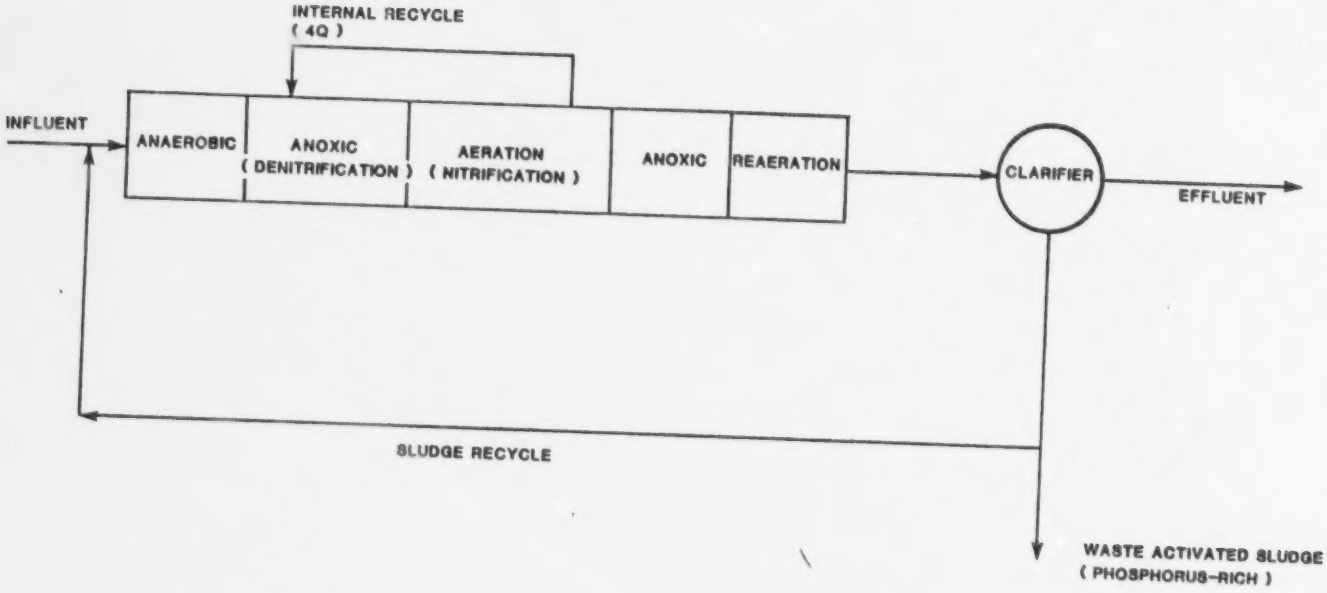

Figure 4. Bardenpho Process Flow Diagram

chemicals, such as alum or ferric salts, are added to polish the effluent phosphorus to below 1 mg/L. Because of the liquid detention times and SRT required for nitrification and denitrification, a relatively high-quality effluent in terms of BOD, suspended solids, and ammonium nitrogen concentrations is possible. The resultant SRT provides an aerobically-stabilized sludge that has been disposed of without further stabilization (18).

The original process in the early 1970's was a single-sludge, four-stage (anoxic-aeration-anoxic-reaeration) system intended for nitrogen removal by biological nitrification and denitrification. The modified Bardenpho process is a five-stage system, with an anaerobic stage added ahead of the original four-stage system for biological phosphorus removal (see Figure 4). Over 30 wastewater treatment plants employing the Bardenpho process for both phosphorus and nitrogen removal have been designed or operated in South Africa (19). The first facility employing this process in the U.S. is the 5,300 m^3/d (1.4 mgd) plant located in Palmetto, Florida. Another Bardenpho system, the 3,200 m^3/d (0.85 mgd) plant in Pluckemin, New Jersey, started operation in late 1982. The first Bardenpho system in Canada is the 60,600 m^3/d (6 mgd) facility in Kelowna, British Columbia, which started operation in mid-1982. The results of findings from the pilot and plant-scale tests are summarized as follows:

- Bardenpho is a promising process for removal of both phosphorus and nitrogen, although limited operating data from the existing plants show inconsistencies in plant performance.

- Many plants in South Africa produce variable concentrations of effluent phosphorus possibly due to a combination of reasons, such as weak wastewater strength in the feed, high TKN-to-carbon ratio, and low plant flow relative to design capacity.

- The capability of the process to consistently produce total phosphorus of less than 2 mg/L, or ortho phosphate of less than 1 mg/L as P, remains to be demonstrated. At Palmetto, Florida, the average total phosphorus concentration during the period between April and September 1980 was 2.2. mg/L after effluent filters. Addition of a small dose of alum was necessary to reduce the total phosphorus to 0.8 mg/L (18).

- At the Palmetto plant, the polishing filters remove only 3 to 4 mg/L of suspended solids. The suspended solids concentrations in the clarifier effluent are very low (average of less than 5 mg/L) before final filtration treatment, due to the very low sludge volume index (SVI) and rapid sludge settling characteristics. This plant maintains a solids residence time (SRT) of approximately 20 days, which is in the low range of 20 to 40 days typically found in the Bardenpho process.

- Problems encountered during the start-up period at the Palmetto facility were related to the internal recycle pumps. Without the internal recycle, effluent nitrate concentrations exceeded 8 to 10

mg/L, which caused biological phosphorus removal to decrease markedly to less than 50 percent. This was actually a mechanical problem rather than one related to the process itself. Once the recycle pumps were operable, the effluent nitrate concentration decreased and phosphorus removal improved.

As in the case of the PhoStrip and A/O processes, the equipment used in the Bardenpho process includes the conventional facilities of concrete or steel tanks, mixers, aerators, clarifiers, and pumps.

FUTURE DIRECTIONS

All three proprietary processes for biological removal of phosphorus are based on the mechanisms that use anaerobic treatment to pre-condition the microorganisms for subsequent enhanced uptake of phosphorus under aerobic conditions. Although significant data and experience have been obtained to substantiate the validity of the fundamental concept, numerous complex factors affecting the performance of the three different systems are not yet fully understood. Some of the more important aspects of research needs are:

- Basic studies involving organisms selection, physiological states, survival, and the direct impact of the anaerobic zone must be conducted before biologically removing phosphorus can be understood fully.

- Current design of the anaerobic section in each of the three proprietary processes appears to be empirical, and there is a lack of rational basis for sizing the anaerobic stage.

- The three processes are capable of producing effluent TP of less than 2 mg/L however, effluent TP concentrations of 1 to 2 mg/L appear in the marginal area that can hardly be predicted with certainty. The TP consists of soluble phosphorus as well as phosphorus associated with the suspended solids form. The soluble phosphorus in the effluent is related to the performance of the process employed, whereas the phosphorus in the solids form is related to the settling characteristics of sludge maintained in the system. Further research is necessary to develop a better basis for predicting effluent quality under various operating conditions and wastewater characteristics.

In addition to the three major proprietary processes discussed in this paper, a number of other modifications to the biological phosphorus removal system have been proposed. They include:

- The UTC (University of Capetown) process described by Siebritz, Ekama and Marais (20) for application to wastewaters with relatively high total Kjeldahl nitrogen to chemical oxygen demand (TKN/COD) ratios.

- The "safe" design optimization approach proposed by Mulbarger and Prober (21), which can be various combinations of primary chemical

treatment, anaerobic and aerobic contacting as in the A/O, PhoStrip with lime addition, and metal salts addition in the aeration basin for polishing phosphorus to low levels.

- The biological phosphorus removal with "roughing" chemical treatment proposed by Stensel (18), which is a modified anaerobic contactor design similar to a combination of the Bardenpho or A/O with the PhoStrip system.

- Phosphorus removal in a Sequencing Batch Reactor (SBR) developed by Dr. Irvine and coworkers at the University of Notre Dame (22).

- Phosphorus removal in oxidation ditch systems developed and marketed by the Kruger Company, Krogshojvej 29, P.O. Box 79, DK-2880 Bagsvaerd, Denmark (23).

SUMMARY

All three proprietary processes have been demonstrated as capable of removing phosphorus from the 4- to 12-mg/L range normally found in municipal wastewaters down to the 1- to 2-mg/L range as total phosphorus (TP). It is important to consider effluent limitations in each specific case to determine the applicability of each process. The risk involved in using any of these processes is not in its complete failure, but in its capability to meet a specific set of effluent limitations. For example, the Great Lakes and Florida-Tampa Bay regions call for effluent limitations of 1 mg/L as TP, and some areas in south Africa have a standard of less than 1 mg/L of orthophosphate as P. Since these processes are often "marginal" in producing effluent quality of less than 1 to 2 mg/L as TP, or 1 mg/L as PO_4-P, other provisions, such as supplemental mineral addition to precipitate residual phosphorus and/or effluent filters, may be necessary unless the reliability of the selected processes is demonstrated by treatability tests or pilot-plant data for a specific case.

Since PhoStrip, A/O, and Bardenpho are proprietary processes, typical design parameters and other considerations important to each should be sought when designing a specific biological system to remove phosphorus. The names and addresses of the marketing agents are given in Appendix A.

CONCLUSION

Many field-scale studies conducted indicate that several patented biological processes are quite successful in removing phosphorus, in a consistent manner, to meet a variety of effluent requirements. Research in full understanding of removal mechanism and in the extension of the experience to different biological processes continues. With a well prepared engineering analysis, biological phosphorus removal may provide the optimun solution to phosphorus control in many municipal wastewater treatment plants.

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APPENDIX A

MARKETING INFORMATION

The PhoStrip process was marketed by Biospherics, Inc. until 1974 when Union Carbide purchased the Levin patent. Biospherics reacquired the PhoStrip rights in 1981, and is presently marketing the process at the following address:

Biospherics Incorporated
4928 Wyaconda Road
Rockville, Maryland 20852

Telephone: 301-770-7700

Additional information on A/O can be obtained from the following address:

Environmental Products Department
Air Products and Chemicals, Inc.
Box 538
Allentown, Pennsylvania 18105

Telephone: 215-481-4911

The Bardenpho process is marketed in the United States by Envirotech at the following address:

EIMCO Process Machinery Division
Envirotech Corporation
669 West Second South
P.O. Box 300
Salt Lake City, Utah 84110

Telephone: 801-526-2000